

POČETNO STANJE NAPONA CEVI KOTLA ZA OCENU INTEGRITETA KONSTRUKCIJE INITIAL STRESS STATE OF BOILER TUBES FOR STRUCTURAL INTEGRITY ASSESSMENT

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Ključne reči

- parni kotao
- greške
- eksperiment
- stanje napona
- podobnost za upotrebu

Izvod

Zbog uočenih nedostataka zahtevana su dodatna ispitivanja radi provere stanja napona i deformacija pri prijemu novog kotla. Zaostali naponi su izmereni metodom bušenja rupa u kritičnim zonama doboša kotla i oštećenih cevi. Promena stanja za vreme i posle probnog ispitivanja vodenim pritiskom je praćena mernim trakama i akustičnom emisijom. Na taj način je utvrđeno početno (nulto) stanje napona kotla pre puštanja u rad.

Početni nivo zaostalih napona (39% do 44% napona tečenja) je posle ispitivanja pritiskom smanjen na 32%, kao posledica preraspodele napona. Naponi proračunati na osnovu izmerenih deformacija su elastični, manji od 99,3 MPa na dobošu kotla i od 66 MPa na kritičnoj cevi 52. Merenja akustične emisije su to potvrdila.

Izvršena ispitivanja i analize pokazala su da se kotao može primiti kao podoban za upotrebu. U toku eksploatacije stanje kotla se može proceniti poređenjem sa početnim stanjem napona.

UVOD

U mnogim slučajevima se otkazi kotlova u eksploataciji, ponekad i znatno pre isteka projektnog veka, ne mogu objasniti samo dejstvom radnih uslova (pritisak i temperatura), već se mora analizirati i uticaj unetih početnih grešaka, /1/.

U cilju povećanja kapaciteta proizvodnje vodene pare u Rafineriji nafte Pančevo instaliran je novi kotao od 110 t/h. Vizuelnim pregledom je uočena nesaosnost cevi 13, izrađene od čelika St 35.8/I, nastala tokom montaže. Takođe je u gornjem delu kotla uočena, zbog plastične deformacije, iskrivljena cev 52, izrađena od istog čelika. Da bi se utvrdila „podobnost za upotrebu“ kotla sa uočenim greškama, zahtevana su dodatna ispitivanja radi procene stanja napona i deformacija u kritičnim zonama u toku probnih ispitivanja pritiskom hladne vode. Radi poređenja analizirano je i ponašanje neoštećene cevi 12. Da bi se izbegla promena stanja kotla ova ispitivanja je trebalo obaviti sa spoljnje strane, metodama koje neće ugroziti integritet cevi kotla. Zahtevano je da se podnese izveštaj o rezultatima dobijenim pre, tokom i posle probnog ispitivanja pritiskom, zajedno sa preporukama za postupak popravke, ako bude potrebna.

Keywords

- steam boiler
- defects
- experiment
- stress state
- fitness-for-purpose

Abstract

Due to detected deficiencies, additional tests were requested for checking the stress-strain state in accepting the new boiler. Residual stresses were measured by hole drilling method in critical zones of boiler drum and damaged tubes. The change of state during and after water pressure proof test was monitored by strain gauges and acoustic emission. In this way, initial (nil) stress state was established before placing the boiler into service.

The initial level of residual stresses (39% to 44% of yield stress) had reduced to 32% after pressure testing, as a consequence of stress redistribution. Stresses calculated based on measured strains are elastic, lower than 99.3 MPa in boiler drum and less than 66 MPa on critical tube 52. This was confirmed by acoustic emission measurements.

Performed tests and analyses showed that boiler can be accepted as fit for service. During exploitation the boiler state can be evaluated comparing to the initial stress state.

INTRODUCTION

In many cases of in-service boiler failures, some well before the end of designed life cannot be explained only by applied operating condition (pressure and temperature), but effect of induced initial damages should also be analyzed, /1/.

In order to increase steam production capacity in Oil Refinery Pančevo, a new 110 t/h boiler was installed. Misalignment of tube 13, made of St 35.8/I steel, is detected visually, and is caused during assembly. Also, tube 52 in the upper part of boiler, made of the same steel, was distorted due to plastic deformation. In order to assess boiler “fitness-for-purpose” with detected defects, additional tests were requested for evaluating the stress and strain state in critical zones during pressure proof test by cold water. For sake of comparison, the behaviour of undamaged tube 12 is also analyzed. These tests have to be performed from the outside in order to avoid change in boiler state by applying methods that will not jeopardize boiler tube integrity. It was required to report test results obtained before, during and after pressure proof tests, together with recommendations for repair procedure, if necessary.

Prihvaćeno je da se izmere zaostali naponi pomoću mernih traka metodom bušenja rupa, da se proračunaju naponi, i da se promena stanja napona prati metodom akustične emisije, /2,3/. Ovim se ispitivanjima može utvrditi i početno (nulto) stanje napona pri prijemu kotla. Promena tog stanja u toku eksploatacije može ukazati na ubrzani razvoj oštećenja i poslužiti za procenu preostalog veka kotla.

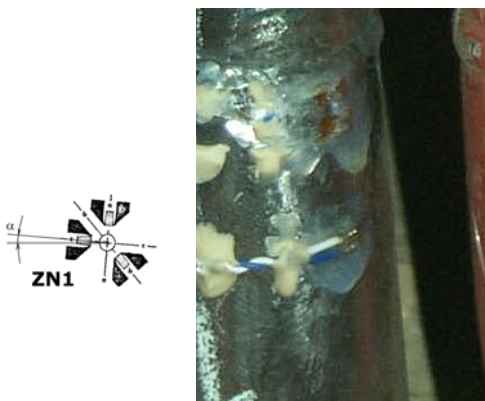
ISPITIVANJE ZAOSTALIH NAPONA

Zaostali naponi su određeni metodom bušenja rupa /4,5/. Korišćene su HOTTINGER rozete mernih traka tipa 1,5/120 RY 61. Kompenzacija temperaturnih promena je izvršena sa 3 merne trake 6/120 LY 11. Merna mesta su tako izabrana da se dobije uvid u raspodelu zaostalih napona u kritičnim zonama cevi kotla. Položaj mernih traka je prikazan na sl. 1. za merno mesto 1 na cevi 52 (1. rozeta). Na mernom mestu 2 na cevi 13 su merenja izvedena pre (rozete ZN1 i ZN2) i posle probnog ispitivanja pritiskom (rozete ZN3 i ZN4), sl. 2. Merna traka „1“ je uzeta kao referentni pravac, sl. 3.

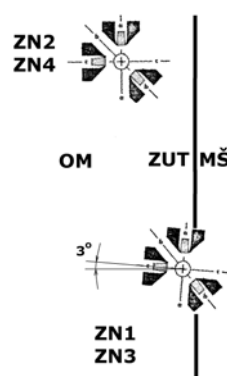
It was agreed to measure residual stresses by applying strain gauges by hole drilling method, calculate stresses, and monitor the stress state by acoustic emission method, /2,3/. This test allows to establish initial (nil) stress state at boiler acceptance. The change of this state during operation can indicate fast damage development and can be used for boiler residual life assessment.

RESIDUAL STRESS TESTS

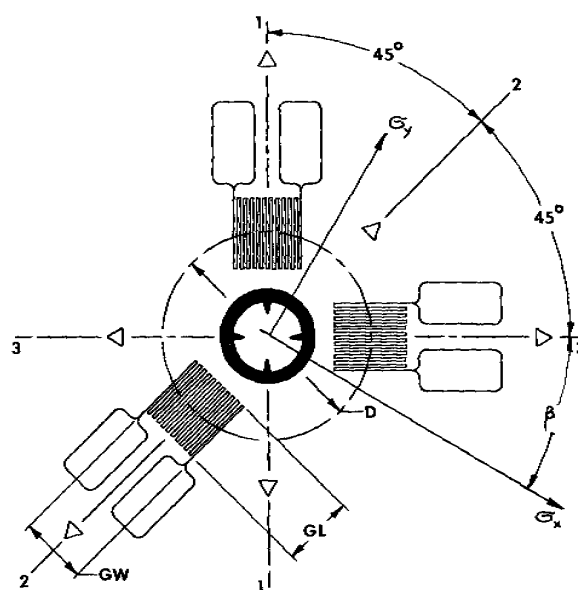
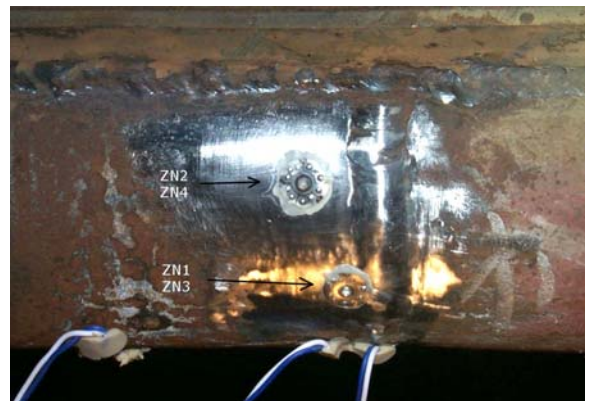
Residual stresses are determined by hole drilling method, /4,5/. Strain gauge rosettes HOTTINGER type 1,5/120 RY 61 are used. Temperature change is compensated by 3 strain gauges 6/120 LY 11. Measuring locations are chosen to get an insight in residual stress distribution in critical zones of boiler. Strain gauge location is presented in Fig. 1 for measuring location 1 on tube 52 (1 rosette). On measuring location 2, tube 13, measurements were performed before (rosettes ZN1 and ZN2) and after pressure proof test (rosettes ZN3 and ZN4), Fig. 2. Strain gauge "1" is selected for referent direction, Fig. 3.



Slika 1. Merno mesto 1 (pri montaži plastično deformisana cev 52)
Figure 1. Measuring location 1 (plastically deformed tube 52 during assembly).



Slika 2. Merno mesto 2 (cev 13 kod koje je pri zavarivanju u procesu montaže došlo do greške nesaosnosti)
Figure 2. Measuring location 2 (tube 13, misalignment defect involved during welding in the assembly process).



Slika 3. Pravci pojedinačnih mernih traka u rozeti 6/120 RY 11 i komponenti normalnog napona σ_x i σ_y
Figure 3. Directions of individual strain gauges in rosette 6/120 RY 11 and of normal stress components σ_x and σ_y .

Cev 13 je prilikom zavarivanja smaknuta, jer pri montaži nije pravilno centrirana. Sa vlasnikom kotla je dogovoreno da se u području zavarenog spoja zaostale deformacije mere pre i posle probnog ispitivanja pritiskom, da bi se proverila pretpostavka da u ovom slučaju dolazi do preraspodele zaostalih napona po zapremini ispitivanog materijala zbog male dužine cevi 13.

Deformacije oslobođene pri bušenju rupe specijalno projektovanim alatom se registruju elektronskim uređajem UPM 40 na osnovu pokazivanja mernih traka u rozeti: $\Delta\varepsilon_a$ za mernu traku 1, $\Delta\varepsilon_b$ za mernu traku 2 i $\Delta\varepsilon_c$ za mernu traku 3 (sl. 3). Dobijeni rezultati za komponente deformacije omogućavaju da se odrede veličine glavnih normalnih napona σ_1 i σ_2 primenom formule:

$$\sigma_{1,2} = -A^* (\Delta\varepsilon_a + \Delta\varepsilon_c) \pm B^* \sqrt{(\Delta\varepsilon_a + \Delta\varepsilon_c - 2\Delta\varepsilon_b)^2 + (\Delta\varepsilon_c - \Delta\varepsilon_a)^2} \quad (1)$$

Vrednosti za koeficijente A^* i B^* su date u tab. 1 za različite module elastičnosti, E , i Poasonove koeficijente, ν , /1/. Ove vrednosti se odnose na geometrijske parametre rozete RY 61 i prečnik rupe $2a = 1,5$ mm.

Tube 13 is dispositioned during welding, since it was not properly centred in the assembly. The boiler owner agreed to measure residual stresses in the region of welded joint before and after pressure proof test, in order to check the assumption that in this case residual stress redistribution had taken place in the tested volume of material due from short length of tube 13.

The strains, relaxed during hole drilling by specially designed tool, are registered through electronic device UPM 40 based on strain gauge indications in the rosette: $\Delta\varepsilon_a$ for strain gauge 1, $\Delta\varepsilon_b$ for strain gauge 2 and $\Delta\varepsilon_c$ for strain gauge 3 (Fig. 3). The obtained results for strain components enabled determining values of principal normal stresses σ_1 and σ_2 by using the formula:

Values for A^* and B^* are given in Table 1 for different elasticity modules, E , and Poisson's ratios, ν , /1/. These values refer to geometric parameters of rosette RY61 and hole diameter $2a = 1.5$ mm.

Tabela 1. Vrednosti koeficijenata A^* i B^*
Table 1. Values of A^* and B^* coefficients

E , GPa	A^*			B^*		
	$\nu=0.26$	$\nu=0.30$	$\nu=0.34$	$\nu=0.26$	$\nu=0.30$	$\nu=0.34$
60	251420	243684	236410	88074	88389	88705
90	377131	365526	354615	132111	132583	133058
120	502841	487369	472821	176148	176777	177411
150	628551	609211	591025	220185	220972	221764
180	754262	731053	709231	264222	265166	266116
210	879972	852896	827436	308259	309360	310049
240	1005682	974738	945641	352297	353555	354822

Međusobno upravni pravci glavnih normalnih napona σ_1 i σ_2 su određeni uglom θ :

$$\tan 2\theta = \frac{\Delta\varepsilon_a + \Delta\varepsilon_c - 2\Delta\varepsilon_b}{\Delta\varepsilon_c - \Delta\varepsilon_a}; \quad \theta = \frac{1}{2} \arctan \frac{\Delta\varepsilon_a + \Delta\varepsilon_c - 2\Delta\varepsilon_b}{\Delta\varepsilon_c - \Delta\varepsilon_a} \quad (2)$$

Mutually perpendicular directions of principal normal stresses σ_1 and σ_2 are determined by angle θ .

REZULTATI ISPITIVANJA ZAOSTALIH NAPONA

Rezultati merenja zaostalih napona za mesto 1 (cev 52) su dati u tab. 2, a za mesto 2 (cev 13) u tab. 3. U tab. 2 i 3 je sa θ_1 obeležen ugao maksimalnog glavnog zaostalog napona u odnosu na uzdužnu osu cevi.

RESIDUAL STRESS TEST RESULTS

Results of residual stress measurement in location 1 (tube 52) are given in Table 2, and in location 2 (tube 13), in Table 2. Symbol θ_1 in Tables 2 and 3 is the angle between maximal principal residual stress and tube longitudinal axis.

Tabela 2. Rezultati merenja zaostalih napona na mestu 1 (cev 52)
Table 2. Residual stress measuring results in location 1 (tube 52).

Merni položaj Measuring location	Merna traka Strain gauge			Napon, MPa Stress, MPa		Ugao, ° Angle, °
	1	2	3	σ_1	σ_2	θ_1
ZN1	-65	-88	-110	163.2	135.3	-0.6

Tabela 3. Rezultati merenja zaostalih napona na mestu 2 (cev 13) pre probnog ispitivanja pritiskom
Table 3. Residual stress measuring results in location 2 (tube 13) before pressure proof test.

Merni položaj Measuring location	Merna traka Strain gauge			Napon, MPa Stress, MPa		Ugao, ° Angle, °
	1	2	3	σ_1	σ_2	θ_1
ZN1	-37	-79	-108	146.0	101.3	-5.2
ZN2	-43	-71	-103	143.1	105.9	1.9

Tabela 4. Rezultati merenja zaostalih napona na mestu 2 (cev 13) posle probnog ispitivanja pritiskom
Table 4. Residual stress measuring results in location 2 (tube 13) after pressure proof test.

Merni položaj	Merna traka			Napon, MPa		Ugao, °
Measuring location	Strain gauge			Stress, MPa		Angle, °
	1	2	3	σ_1	σ_2	θ_1
ZN3	-27	-58	-86	114.7	78.1	-1.5
ZN4	-35	-67	-90	123.9	89.4	-4.6

PRAĆENJE DEFORMACIJA PRI PROBNOM ISPITIVANJU PRITISKOM I DOBIJENI REZULTATI

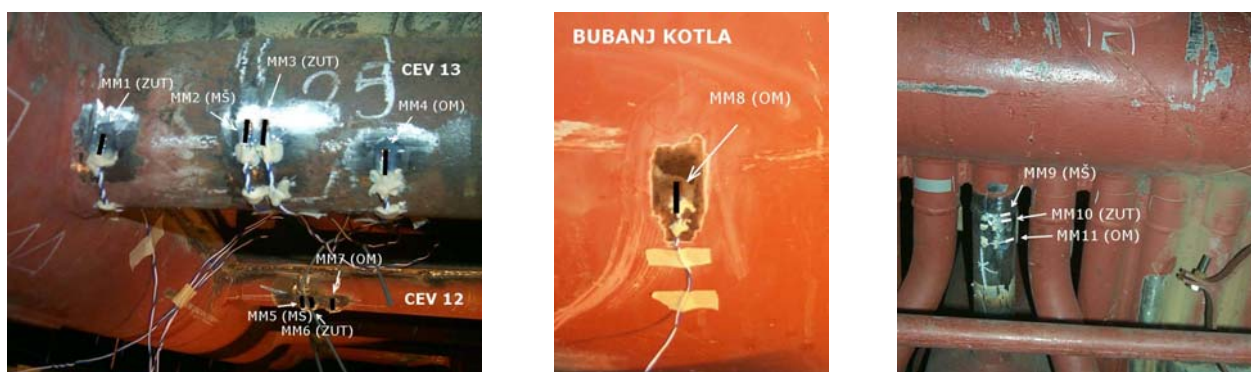
Promena deformacija tokom probnog ispitivanja pritiskom je praćena pomoću pojedinačnih mernih traka 10/120 LY 11 HOTTINGER. Kompenzacija temperature je izvedena sa 4 iste merne trake. Merne zone su izabrane tako da se dobije uvid u raspodelu glavnih napona i oceni maksimalni napon u području grešaka uočenih pri montaži, /6,7/. Radi poređenja, ispitano je i ponašanje neoštećene cevi 12. Definisane su četiri zone merenja. Na sl. 4 su prikazane zone i merna mesta:

- zona I, na cevi 13, mesta 1 do 4, i zona II na cevi 12, mesta 5 do 7;
- zona III na dobošu kotla, merno mesto 8;
- zona IV na cevi 52, merna mesta 9 do 11.

STRAIN MONITORING DURING PRESSURE PROOF TEST AND THE OBTAINED RESULTS

Change of deformation during pressure proof testing was monitored by using individual strain gauges 10/120 LY 11 HOTTINGER. Temperature compensation was performed by four similar gauges. Measuring zones were selected with the owner to gain insight in principal stress and to assess maximal stress in defected regions detected during assembly, /6,7/. The behaviour of undamaged tube 12 is also tested for comparison. Four measuring zones were defined. Zones and measuring locations are presented in Fig. 4:

- zone I on tube 13, locations 1 to 4, and zone II on tube 12, locations 5 to 7;
- zone III on boiler drum, measuring location 8;
- zone IV on tube 52, measuring locations 9 to 11.



Slika 4. Zone i merna mesta za praćenje deformacija pri probnom ispitivanju pritiskom
Figure 4. Zones and measuring locations for monitoring strains during pressure proof test.

- Zona I, cev 13, merna mesta 1 do 4, zona II, cev 12, merna mesta 5 do 7
- Zona III, doboš kotla, merno mesto 8
- Zona IV, cev 52, merna mesta 9 do 11

Deformacije su merene stepenasto na unapred zadatom nivou pritiska do dostizanja maksimalnog pritiska 71,5 bar tokom probnog ispitivanja pritiskom hladne vode. Glavni normalni naponi, σ_1 , su izračunati na osnovu izmerenih deformacija korišćenjem formule

$$\sigma_1 = E \cdot \varepsilon \quad (3)$$

Zavisnost glavnog normalnog napona, σ_1 , od delujućeg pritiska, p , za sva merna mesta, prikazana je na sl. 5.

ISPITIVANJE AKUSTIČNOM EMISIJOM

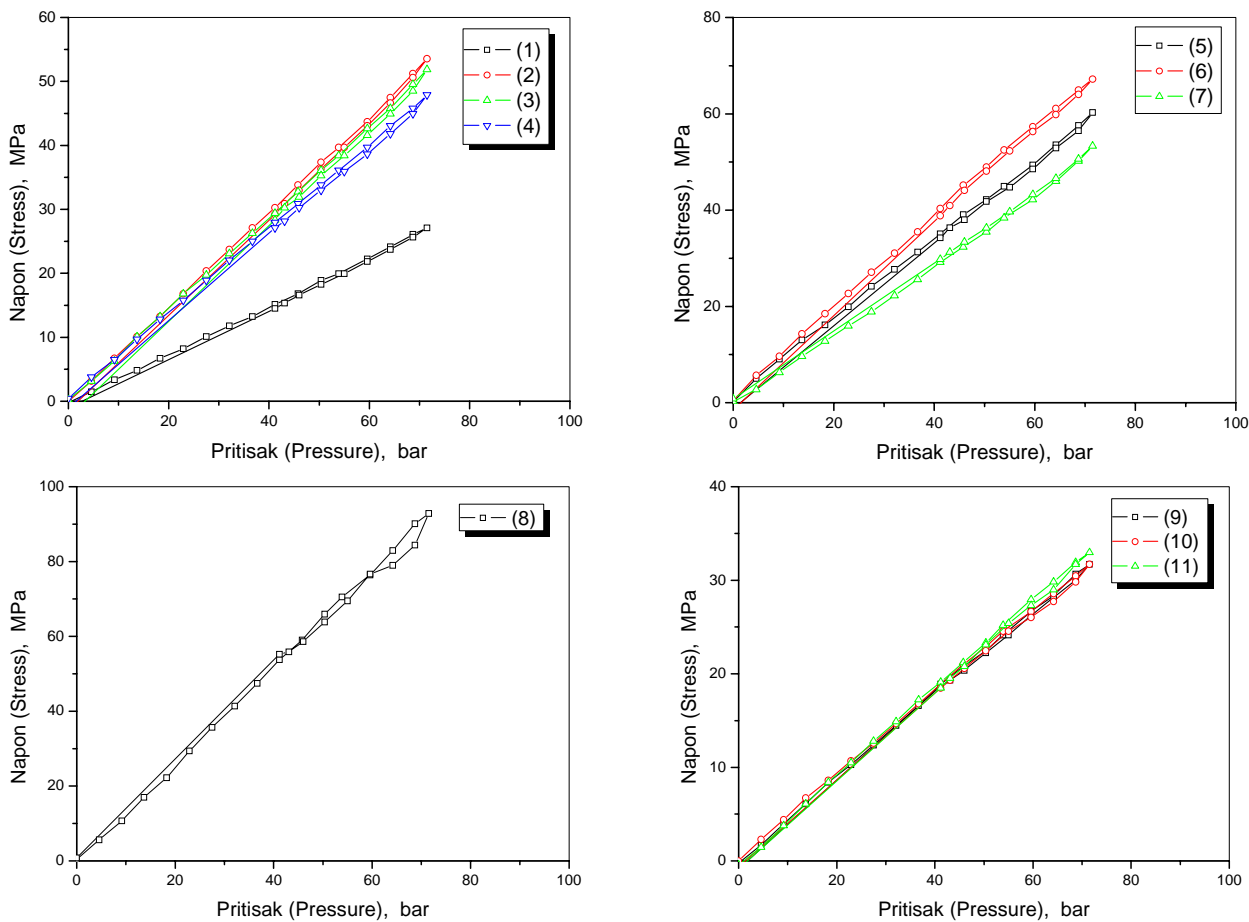
Za beleženje i obradu signala akustične emisije (AE) je korišćen detektor AE, čija je blok shema prikazana na sl. 6, /8/. Na osnovu iskustva za obradu AE signala je odabran postupak zasnovan na brojanju oscilacija zabeleženih senzorom. Dobijeni rezultati su potvrdili elastično ponašanje materijala do maksimalnog pritiska ispitivanja, kao što je za doboš bubnja pokazano na sl. 7, radi ilustracije.

Strains are measured step-wise at predetermined pressure level up to maximal stress of 71.5 bar that is achieved in the cold water pressure proof test. Principal normal stresses, σ_1 , are calculated based on measured strains, by using the formula

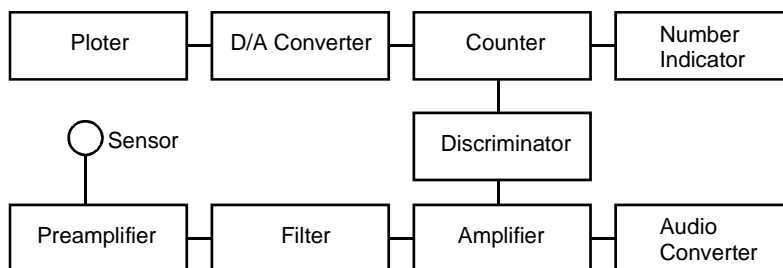
The dependence of principal normal stresses, σ_1 , vs. applied pressure, p , for all measuring locations, is given in Fig. 5.

TESTING BY ACOUSTIC EMISSION

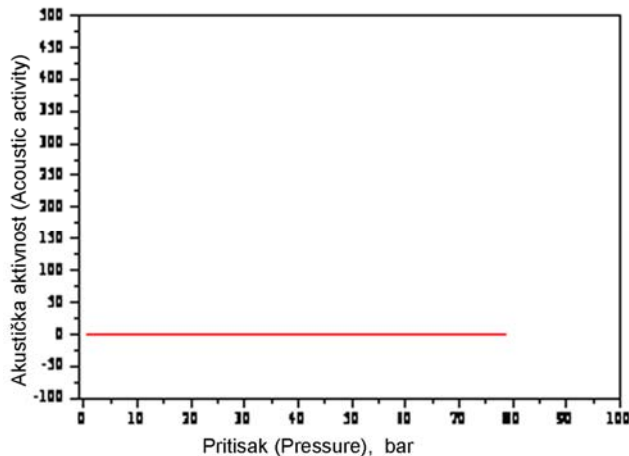
Acoustic emission (AE) signal recording and processing is made by AE detector, whose block scheme is presented in Fig. 6, /8/. Based on experience, a ring down count procedure is selected for AE signal processing. The obtained results have confirmed material elastic behaviour up to maximal test pressure, as presented for boiler drum in Fig. 7, as an example.



Slika 5. Zavisnost napon–pritisak
Figure 5. Dependence stress–pressure.



Slika 6. Blok shema za detekciju i analizu signala AE
Figure 6. Block scheme for acoustic emission signal detection and analysis.



Slika 7. Zavisnost akustična aktivnost–pritisak
Figure 7. Dependence acoustic activity–pressure.

Za obradu ovako dobijenog signala, u korišćenoj metodi signal se propušta kroz diskriminator na čijem se izlazu nalazi brojač. Svaki put kada amplituda signala premaši unapred zadati nivo, stanje na brojaču se poveća za jedan. Akustična aktivnost je broj impulsa u određenom vremenskom intervalu, a ukupna emisija je sumarni broj impulsa tokom eksperimenta, /9/. Nivo odlučivanja je eksperimentalno određen na osnovu kalibracione krive za dati materijal. Kalibraciona kriva se konstruiše na osnovu rezultata ispitivanja epruvete za zatezanje.

Cilj ovog ispitivanja je definisanje nivoa odlučivanja za pojavu plastične deformacije materijala. U ovom slučaju nivo odlučivanja je definisan ispitivanjem na sobnoj temperaturi epruvete na zatezanje, izrađene od materijala iste klase (čelik za rad na povišenim temperaturama) od koga je napravljen doboš parnog kotla.

Ako je nivo odlučivanja postavljen suviše nisko, dolazi se u oblast u kojoj nije moguće izdvojiti šum od korisnog signala. Međutim, ako je nivo odlučivanja postavljen suviše visoko, postoji opasnost da se tokom eksperimenta ne dobije nikakav AE signal. Zbog toga je za realizaciju ovakvog eksperimenta potrebno iskustvo i poznavanje materijala od kojeg je napravljen doboš kotla.

Kao sonda, korišćena je piezoelektrična keramička pločica BMF 10P-5 rezonantne učestanosti 180 kHz. Ukupno pojačanje signala AE bilo je isto od početka ispitivanja i iznosilo je 10×10000 . Frekventni odziv pojačivačkog stepena od 100 kHz do 3 MHz snižen je upotrebom filtera koji nema uticaja na ukupno pojačanje, tj. na rezonantnu oblast senzora. Na taj način su otklonjene smetnje u sistemu, prouzrokovane radom drugih uređaja, /10/.

Sonda detektora AE je instalirana na gornjem dobošu kotla (parni). Sonda je koaksijalnim kablom vezana za AE detektor. Izlazni AE signal se preko detektora AE i brojača registruje kao broj oscilacija zabeleženih senzorom.

Pri ispitivanju zavarenih konstrukcija, a tu spada i doboš kotla, sonda detektora se postavlja u blizini zavarenog spoja koji je zbog heterogenosti mikrostrukture kritično mesto na konstrukciji. Heterogenost mikrostrukture zavarenog spoja i greške zavarivanja su uzročnici pojave prslina, koje mogu u eksploataciji da dovedu do otkaza i katastrofalnih lomova.

Upravo akustična emisija, kao jedina aktivna metoda, je u stanju da na vreme otkrije nepovoljni deformacijski proces i pojavu ili rast prslina, /11/.

ANALIZA REZULTATA

Na cevi 52 izmeren je zaostali napon nivoa 44% napona tečenja. U ZUT i OM zavarenog spoja cevi 13 je izmeren zaostali napon nivoa 39% napona tečenja. Posle probnog ispitivanja pritiskom, zaostali napon je opao na 32% napona tečenja, jer je došlo do otpuštanja zaostalih napona plastičnom deformacijom u oblasti koncentracije napona.

Proračun napona na osnovu mikrodeformacija, izmerenih mernim trakama tokom probnog ispitivanja pritiskom je pokazalo elastično ponašanje materijala (sl. 5) u svim zonama cevi i doboša kotla, sa maksimalnom vrednošću na dobošu 99,3 MPa, a 66 MPa na cevi 52.

Izmerene deformacije na rozetama i izračunati zaostali naponi (naponi σ_1 i σ_2) pokazuju relativno visoke vrednosti

Processing the obtained signal in this way in the applied method assumes transmitting through the discriminator ended by a counter. Every time when the signal amplitude exceeds the predetermined level, the state on the counter increases by one. Acoustic activity is a number of pulses in a specified time interval, and total emission is the number of cumulative pulses in the experiment, /9/. The decision level is defined experimentally, based on the calibration curve for the given material. The calibration curve is designed based on test results obtained from tensile specimen.

The aim of this test is to define the decision level for initiation of plastic deformation. In this case, the decision level is defined by testing a tensile specimen prepared of the same class material (high temperature steel) at room temperature, of which the boiler drum is produced.

If the decision level is set too low, one enters the region where it is not possible to distinguish noise from the useful signal. However, if the decision level is set too high, there is risk in not being able to detect any AE signal in the experiment. Owing to this, the realisation of such an experiment requires experience and good knowledge of material characteristics of the boiler drum material.

The piezoelectric ceramic plate BMF 10P-5 of resonant frequency 180 kHz is used as a sensor. The total AE signal amplification was the same from the beginning of the tests and amounted to 10×10000 . The frequency response of the amplifier from 100 kHz to 3 MHz was decreased by the used filter that did not affect total amplification, i.e. the sensor resonant range. In this way, system disturbances caused by the operation of other devices was avoided, /10/.

The AE detector sensor is installed on upper boiler (steam) drum. The sensor is connected to AE detector with co-axial cable. The outgoing AE signal is registered by the oscillating ring down count through AE detector and counter.

Testing of welded joints, including boiler drums, requires that the detector sensor is placed near to the welded joint, as a critical region in the structure due to the heterogeneity of microstructure. Both microstructural heterogeneity in the welded joint and welding defects are causes for crack initiation that may produce failures and catastrophic fracture in exploitation.

Acoustic emission, as the only active method, is capable in detecting an undesirable deformation process and crack initiation or propagation in acceptable time, /11/.

ANALYSIS OF RESULTS

The measured residual stress is at 44% yield strength level on tube 52. The measured residual stress was 39% of yield strength in welded joint HAZ and BM of tube 13. Due to residual stress relaxation by plastic deformation in the stress concentration region, the residual stress has reduced to 32% of yield strength, after the proof pressure test.

Stress calculations from microstrains measured by strain gauges during the pressure proof test showed elastic behaviour of material (Fig. 5) in all zones of tubes and boiler drum, with maximal value of 99.3 MPa in boiler drum and 66 MPa in tube 52.

Strains measured on rosettes and the calculated residual stresses (σ_1 and σ_2) show relatively high values ($\sigma_1 = 163$ MPa

($\sigma_1 = 163$ MPa i $\sigma_2 = 135$ MPa) na mernom mestu 1 (cev 52, tab. 2), što ukazuje da je plastična deformacija cevi značajno uticala na veličinu zaostalih napona. Izračunati zaostali napon na cevi 13 (merno mesto 1 i 2, odnosno merno mesto 3 i 4, tab. 3), su relativno visoki, ali su dosta bliski. Interesantno je da je posle probnog ispitivanja pritiskom došlo do smanjenja zaostalih napona, odnosno, potvrđeno je da je delujući pritisak doveo do preraspodele zaostalih napona.

Izmerene deformacije mernim trakama tokom probnog ispitivanja pritiskom i izračunati glavni naponi pokazuju da ni na jednom mernom mestu nije prekoračen napon tečenja, odnosno, ponašanje materijala je linearno elastično sve do maksimalnog pritiska ispitivanja 71,5 bar. Glavni naponi su niski u svim zonama i kreću se od 26 MPa na mernom mestu 1 (cev 13) do približno 53 MPa na mernom mestu 3 u zoni I, sl. 5a, od 52 MPa na mernom mestu 7 do 66 MPa na mernom mestu 6 u zoni II (cev 12), sl. 5b. Viši naponi na neoštećenju cevi 12 u poređenju sa naponima na cevi 13 pokazuju da uneta greška nesaosnosti cevi 13 nije uticala na integritet konstrukcije, pa se pri prijemu kotla može zanemariti. U zoni IV su glavni naponi dosta niski i ujednačeni kao posledica plastične deformacije cevi 52, sl. 5d. Najveći glavni napon je utvrđen na mernom mestu 8, zona III, sl. 5c, što je i očekivano, jer je merna traka postavljena na osnovni materijal po obimu doboša, u pravcu maksimalnih napona. Vrednosti glavnih napona i na mestima pri montaži utvrđenih grešaka, kao i na mestima gde grešaka nema, su u granicama relativne greške merenja, i niži su od minimalne vrednosti napona tečenja za ugrađeni materijal.

Iz sl. 7 se vidi da pri probnom ispitivanju pritiskom nije bilo akustičke aktivnosti, odnosno, da se nije javila plastična deformacija i da nije došlo do inicijacije i rasta prslina.

Sem toga treba navesti da, tenzometrijskim merenjem deformacija tokom probnog ispitivanja pritiskom pri rastećenju do nultog stanja, sve su merne trake pokazivale negativnu vrednost, odnosno, registrovale su neznatnu relaksaciju napona.

Na osnovu izvedenih ispitivanja i analiza, preporučeno je da se kotao prihvati kao „podoban za upotrebu“.

ZAKLJUČAK

Razmatrajući rezultate merenja i izvedene analize može se zaključiti sledeće.

1. Eksperimentalnim ispitivanjima su dobijene relativno visoke vrednosti zaostalih napona u mernim zonama cevi kotla, ali one ne ugrožavaju integritet kotla u kritičnim područjima na cevima 52 i 13. Probno ispitivanje pritiskom je doveo do uravnoteženja napona njihovom preraspodelom.
2. Izmerene deformacije na mernim trakama i izračunati glavni naponi u zonama merenja pokazuju da pri probnom ispitivanju pritiskom do nivoa od 71,5 bar, materijal cevi i gornjeg doboša kotla se ponaša isključivo elastično.
3. Senzor detektora akustičke emisije pri podizanju pritiska tokom ispitivanja vodenim pritiskom nije registrovao nijednu oscilaciju, što potvrđuje da nije bilo trajnih plastičnih deformacija ili iniciranja i rasta prslina.
4. Uspostavljeno početno stanje napona je od koristi za praćenje ponašanja kotla tokom eksploatacije.

and $\sigma_2 = 135$ MPa) at measuring location 1 (tube 52, Table 2), indicating that tube plastic deformation affects residual stress level. Calculated residual stresses in tube 13 (measuring locations 1 and 2, i.e. 3 and 4, Table 3), are relatively high, but they are quite close. It is interesting that after the pressure proof test, residual stresses were reduced, thus confirming that the applied pressure had caused the redistribution of residual stresses.

Strains measured by strain gauges during pressure proof testing and the calculated principal stresses show that in none of the measuring locations has the yield strength been exceeded, meaning that material behaviour is linear elastic up to the maximal test pressure of 71.5 bar. Principal stresses are low in all zones and ranged from 26 MPa at measuring location 1 (tube 13) to about 53 MPa at measuring location 3 in zone I, Fig. 5a, from 52 MPa in measuring location 7 to 66 MPa in measuring location 6 in zone II (tube 12), Fig. 5b. Higher stresses in undamaged tube 12 compared to stresses on tube 13 shown that the induced defect of the misaligned tube 13 did not affect structural integrity, so it can be disregarded at boiler acceptance. In zone IV, the principal stresses are very low and uniform as a result of plastic deformation in tube 52, Fig. 5d. The maximal principal stress is found at measuring location 8, zone III, Fig. 5c, as expected, since the strain gauge is placed in the hoop direction of maximal strains on the boiler base metal. Principal stress values in regions of detected defects in the assembly, as well as in regions with no defect are within the limits of relative measurement error, and are lower than the minimal yield strength of the built-in material.

As seen from Fig. 7, acoustic activity during pressure proof test was not recorded, meaning that plastic deformation did not occur and crack initiation or propagation did not take place.

Additionally, during the pressure proof test, from unloading to zero state, all strain gauges showed a negative value, and registered insignificant stress relaxation in tensometric strain measurements.

Based on performed tests and analyses it is recommended to accept the boiler as “fit for purpose.”

CONCLUSION

Considering test results and performed analyses one can derive the following conclusions:

1. Relative high residual stress values are obtained in experimental tests in measured zones of boiler tubes, but do not jeopardize boiler integrity in critical regions, in tubes 52 and 13, respectfully. The pressure proof test produced stress equilibrium by redistributing the stresses.
2. Measured strains by strain gauges and calculated principal stresses in measurement zones have shown that in the pressure proof test to the level of 71.5 bar, tube and upper boiler drum materials showed strictly elastic behaviour.
3. The AE detector sensor had not registered any oscillations during the increase of pressure level in the water pressure test, thus confirming that no permanent plastic strains or crack initiation or propagation had taken place.
4. The established initial stress state is useful for monitoring boiler behaviour during exploitation.

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